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Finite Element Investigation of Performance of Composite-Steel Double Lap Adhesive Joint Under Tensile Loading

Abstract

Parametric study of composite-steel double lap joint under tensile loading is performed using finite element modeling. The joint is such that steel is placed between a straight and a curved composite sublaminate. Three joint characteristics including maximum Von Mises stress in adhesive layer, stiffness and weight are investigated. Design curves are provided to study the influence of geometric parameters on the joint behavior to determine the joint performance. The curves illustrate sensitivity of three mentioned joint characteristics to geometric variations. Selected parameters are adhesive thickness, overlap length, composite sublaminates' thickness and stiffness ratio.

Results indicate variation of parameters may have either significant or negligible influence in the performance of the joint. Results also show that variation in geometric parameters does not make monotonous change in the performance of the joint and in some cases rate of the changes may differ. From the prepared curves it can be understood that increase in overlap length and adhesive thickness will decrease maximum Von Mises stress in adhesive layer and global stiffness of the joint. In case of sublaminate thickness decrease in the thickness of straight sublaminate leads to decrease in maximum stress in adhesive layer while the stiffness is increased. For the stiffness ratio an optimized point can be found beyond which maximum stress will increase. Global stiffness of the joint increases by increase in stiffness ratio. Changes in weight of the joints are easily calculated from the geometry and are reported in the text.

Keywords

Adhesive composite-steel joints, finite element analysis, parametric study.

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1 INTRODUCTION

Reduction of fuel consumption and increase in payload are the main requirements of modern ship designs. The first and best solution to achieve these two important goals is to reduce the lightship weight while the required strength of the hull girder is maintained. This has pushed designers to use lighter materials – lower weight/strength ratio – such as composite materials either in laminate or in sandwich configurations. Composite materials have entered marine industry for some decades but they can only be used for small vessels such as pleasure crafts and some naval vessels. This decade is the time for light weight material to take part in construction of larger vessels by replacing various parts of the ship steel or aluminum structures, mainly superstructures, bulkheads, mast and decks that are close to the ship's neutral axis and do not contribute to its longitudinal strength.

There exists some different ways to connect either similar or dissimilar materials. Conventional mechanical connections such as bolt and nuts are preferred as they are easy to design and able to be dismantled. The problem with bolt and nut connection is that they are prone to stress concentration and local failure that will decrease joint quality and joint integrity. Welding is another efficient way to connect material together, but it is only used to connect metallic components. These problems made structural specialists to think for a way to connect dissimilar material, mainly steel to composite. Therefore the idea of connection by means of adhesive material was finally come up as one of the best solutions to connect dissimilar materials. As a general rule for methodical and geometrical design, design of an adhesive joint should be clear, simple and safe.

The newly arisen concept of using composite materials together with metallic structures requires more investigations on the design of proper biomaterial joints (mainly composite to metal joints). For the first step, designers should consider the geometry of the joint as it has direct influence on the load carrying capacity of the joint and manufacturing cost.

In order to design an effective connection between composite parts and metallic structures geometry, loading and usage of the particular parts to be connected should be considered. At the same time, such a joint should fulfill some basic principles and requirements, on the basis of which design and manufacturing of the joint will be done. The most important requirement is adequate mechanical behavior of the joint to ensure the structural integrity of the joined structure under any loading it may carry. Some other characteristics for a joint to be effective are low production and maintenance costs, easy and distinct method of manufacture and application, possibility in automation of the manufacturing processes and finally easily accessible to inspect and repair.

A.P Mouritz et al. (2001) conducted surveys on advanced composite structures for naval ships and submarines in which they studied connection of composite to steel in marine industry for the first time. S.M Clifford et al. (2002) investigated characterization of a prototype joint between GRP and steel for use between a naval GRP superstructure and a steel hull, the prototype is actually a double lap joint between a GRP sandwich panels with balsa core to steel. They found GRP–steel interface to be critical to mechanical performance of the joint and therefore they evaluated effects of surface preparation on the GRP–steel. Results show interfacial toughness to increase greatly with surface roughness for low surface roughness up to a particular roughness above which no further increase is obtained.

Hybrid ship hulls are other concepts in the field of composite-metal joints. S. Barsoum (2003) proposed two hybrid hull designs; in the first one middle section of the hull is made of steel while the bow and stern are made of composite materials and in the second design he proposed an all-composite skin along the entire hull reinforced with stainless steel framing. Jun Cao et al. (2004) proposed two composite sandwich-to-steel joints for hybrid hull - a bonded-bolted joint and a co-infused perforated joint. They used various techniques such as using bolts, secondary bonding, co-infusion, and perforations to increase joint strength. They conducted bending and shear tests investigate strength of proposed joints. They observed excellent strengths for both types of joints. S.W. Boyd et al. (2007) worked on optimizing mechanical behavior of the prototype joint introduced by Clifford. They investigated five geometric parameters: adhesive thickness, core thickness, GRP skin thickness, overlap length and steel thickness.

A recent study by N.G. Tsouvalis and V.A. Karatzas (2010) involved feasibility of a simple double lap joint between steel and composite laminates through both numerical and experimental studies. Effects of overlap length and surface preparation of adherent on tensile strength of the joint are included in investigations. Results show that increase in joint overlap length increases failure load and steel surface preparation method does not affect joint stiffness. They finally proposed a parametric study to be done for optimizing joint behavior.

This study investigates performance of composite-steel joint by means of parametric variation of the geometric joint variables of the joint under tensile loading through finite element simulation. Weight, maximum stress in adhesive layer and global stiffness of the joint are three characteristics under investigation in which influence of adhesive thickness, overlap length, composite sublaminates' thickness and stiffness ratio are studied.

2 MODEL FOR ANALYSIS

2.1 Structural Arrangement and Joint Characteristics

A low stiffness, double lap joint similar to one studied by N.G. Tsouvalis and V.A. Karatzas (2010) is selected. The joint is used typically in marine applications. Figure 1 illustrates the joint schematically. The joint is composed of a steel bar beveled at its right edge and is overlapped from top and bottom by two composite sublaminates. The steel component bevel angle is 45°. Sublaminates covering the steel part join together after the bevel to form the main composite laminate. The joint is clear as the load flux through the joint is obvious and can be easily described; it is effective in axial tension. Assembly of the joint is simple as the number of components which are used in the joint are as low as possible and the joint is easy to manufacture.

All previous studies mentioned earlier in section 1 show that important parameters effecting mechanical behavior of composite-metal adhesive joints are:

- Thickness of adherents
- Adhesive thickness
- Overlapping length
- Composite sublaminates' thicknesses (for double lap and double strap joints)
- Core thickness (in sandwich materials)
- Stiffness ratio
- Metal end shape (ex. bevel angle)

The last two parameters have attracted fewer attentions. All parameters are known from the geometry of the joint except for the stiffness ratio which is defined as:

$$\mathrm{SR} = (\mathrm{Ec} \cdot \mathrm{tc})/(\mathrm{Est} \cdot \mathrm{tst}) \tag{1}$$

Ec and tc are the Young's modulus and thickness of the composite part respectively, and Est and tst are the corresponding properties of the steel adherent.

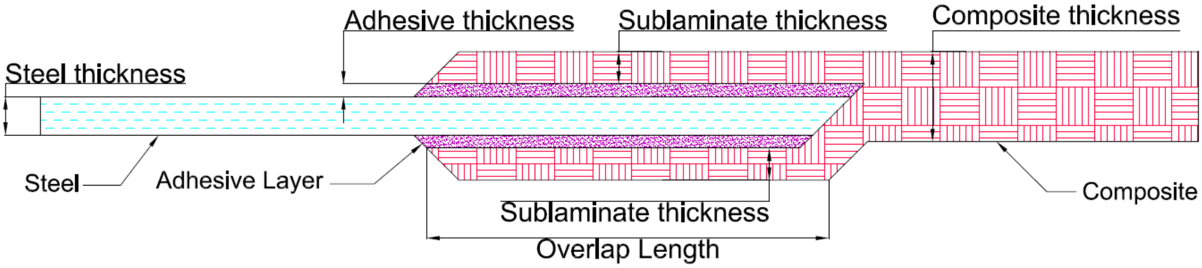

Figure 1: Schematic illustration of the joint.

As discussed earlier, the weight reduction is the main reason for the use of composite materials together with steel in ship hulls. From experimental results of previous study by N.G. Tsouvalis and V.A. Karatzas on tensile loading of the joint, it is known that failure initiates from the free edge of the composite-steel interface and propagates through the adhesive until final debonding so the stresses in the adhesive layer is the source of failure within the joint and thus for improving the performance of the joint, care must be taken in order to reduce the stress in adhesive layer. Finally, stiffness of the joint is considered as it influences the generation of the stress in the adhesive layer of the joint, therefore present study focuses on three joint characteristics:

- Maximum stress in adhesive layer
- Global joint stiffness
- Weight

Variation of four joint parameters including adhesive thickness, overlap length, composite sublaminates' thickness and stiffness ratio are surveyed in order to evaluate their influence on three mentioned joint characteristics. The first three parameters are directly obtained from geometry of the joint but stiffness ratio as defined in section 2 depends on both adherent thicknesses and their mechanical properties (Young's modulus). Mechanical properties are considered to be constant throughout present study and therefore stiffness ratio only depends on adherent thicknesses allowing simultaneous investigation on the effects of adherents on joint behavior.

A series of models are simulated in finite element environment so that maximum stress in adhesive layer and global joint stiffness are calculated from finite element analysis and weight of the joint is calculated from the known dimensions of the joint by having densities of the joint components. Densities of the three component materials are listed in Table 1.

A reference joint is selected as a baseline to calculate variations from. Present study aims to compare variation of joint parameters, therefore results of any certain cases are not reported and all results are presented as a percentage change from the reference joint.

2.2 Finite Element Code and Adopted Elements

In discretization of the joints under study, PLANE82 element is used to perform 2-D analysis in the x-y plane in the finite element code ANSYS 12.0 environment. PLANE82 is defined by eight nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element may be used as a plane element or as an axisymmetric element. It can provide accurate results for mixed (quadrilateral-triangular) automatic meshes and can tolerate irregular shapes without as much loss of accuracy. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. Figure 2 shows PLANE82 element.

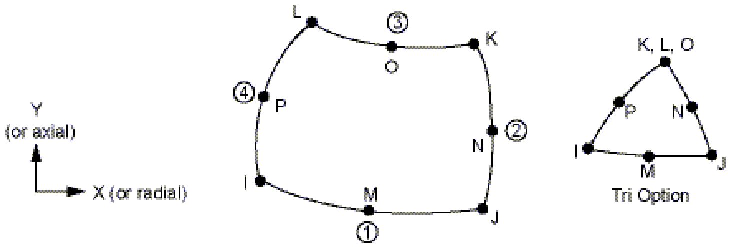

Figure 2: PLANE82 element.

Figure 3 below shows finite element model of the reference joint, cyan and red color represents steel and composite respectively, the adhesive layer is not visible as it is very thin regarding to steel and composite sublaminates. A resin rich area in front of the steel bevel is modeled to account for pile up of bulk resin in front of steel bevel, it is shown in purple.

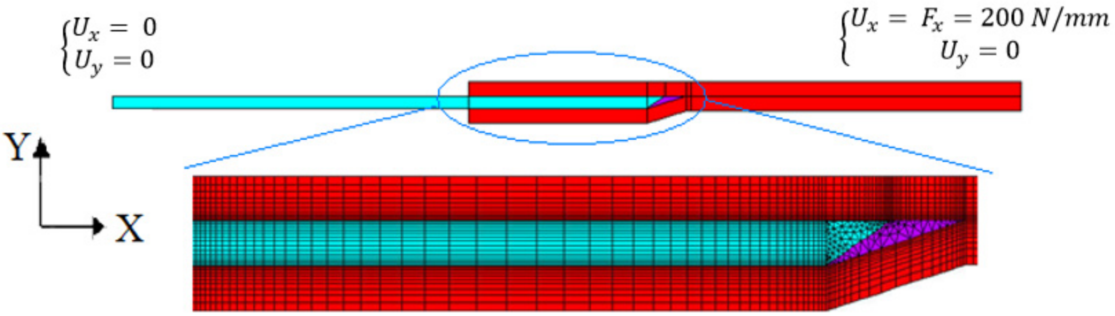

Figure 3: Typical examples of the meshed model (for the reference joint) showing boundary conditions at the joint ends.

2.3 Mechanical Properties of Materials

Components of the model are selected from typical marine materials that can be used to connect composite to metal for marine applications. The composite part is typically glass/epoxy system. Unidirectional E-glass fibers with low viscosity cold cured epoxy are used to make typical glass/epoxy coupon having wrap direction along the length of the specimen and for connecting steel component to composite part same epoxy resin is used. Adhesive and steel are modeled as isotropic material, and the composite part is modeled as linear homogeneous orthotropic material.

Mechanical properties of steel are taken from the specimen manufactured by N.G. Tsouvalis and V.A. Karatzas (2010). Mechanical properties of the composite part are taken from a material characterization test program by Misirlis et al (2003) and resin is low viscosity cold cured epoxy. Mechanical properties for use in finite element analysis are presented in Table 1.

Material Properties	Steel	Resin	Composite
E_x (MPa)	179470	2030	34980
E_y (MPa)	-	-	7741
υ_{xy}	0.29	0.35	0.29
G_{xy} (MPa)	-	-	1817
Density (kg/m^3)	7850	1120	1100

Table 1: Material Properties.

Ex and Ey are modulus of elasticity in x and y directions respectively, υ is poison's ratio and G is shear modulus.

2.4 Boundary and Loading Conditions

Investigations are to be done under tensile loading. Geometry of the joint is such that no symmetry can be found and therefore the whole joint as it sets in the grips of tensile testing machine is modeled. At the end of steel part, X and Y translations of the joint are considered fixed.

In the present research, detailed results and exact replication of the simulations are not mentioned and the results are presented in comparative manner. Therefore a tensile load of 200 N/mm is applied to the joint through the composite end of the joint in X direction alongside its width. The 2-dimensionally-simulated model of the joint explains the Newton per millimeter unit for the applied load. The applied load is considered much smaller than the failure load of the joints so as to avoid failure in the joint. Figure 3 shows boundary condition and applied load of the model in finite element environment.

2.5 N.G. Tsouvalis and V.A. Karatzas Test

N.G. Tsouvalis and V.A. Karatzas (2010) introduced a simple concept composite-steel double lap adhesive joint, which can be simply and easily manufactured using even conventional manufacturing methods of composite materials. They carried out tensile tests to investigate parameters like the overlap length of the joint and the surface preparation of the steel adherent in the joint behavior.

Tests were carried out using typical universal tensile machine. All specimens were subjected to a monotonically increasing tensile loading. Particularly four cases including combination of two overlap lengths and two steel surface preparation methods were considered to investigate their effect on the joint strength. Thus, for each overlap case, two kinds of specimens were manufactured with two different steel surface preparation methods, utilizing sand blasting and air hammer. Side view of a 60 mm overlap joint and a failed specimen can be seen in figure 4.

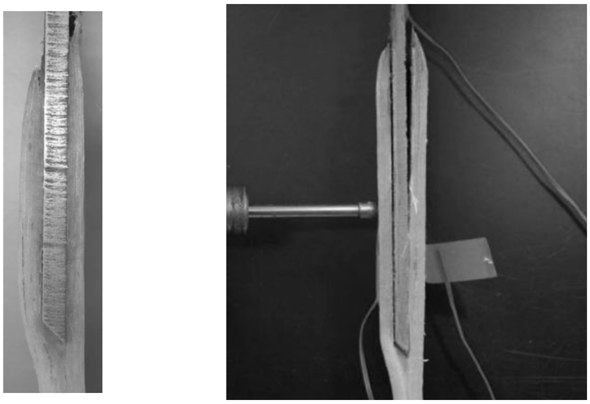

Figure 4: Side view of a 60 mm overlap joint (Left) and a failed specimen (Right).

Time histories of the axial displacement and axial reaction force were recorded during each test. The test results are used herein to validate the finite element modeling and analysis. Figure 5 shows the axial reaction force versus axial displacement diagrams of the specimens with 60 mm overlap length for two different surface preparation methods. As it was mentioned previously, failure of the joint in finite element model is not simulated and analysis is carried out to reflect global stiffness of the join only. N.G. Tsouvalis and V.A. Karatzas (2010) also reported lateral displacement in y-direction in the middle of the overlap area with the aid of a LVDT and axial strains in different parts of the joint using four strain gages. Figure 5 shows a good agreement between the experimental and numerical results.

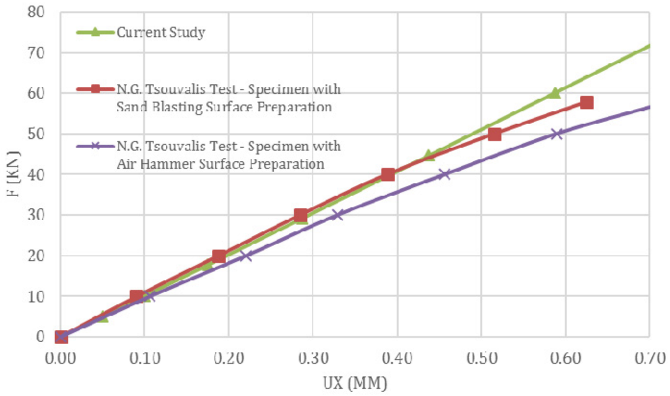

Figure 5: Comparison of experimental results for the axial displacement of the specimen with 60 mm overlap length (N.G. Tsouvalis and V.A. Karatzas 2010) with numerical results of current study.

2.5 Mesh Density Study

FE model consists of 8-node quadrilateral elements except for mesh refinement areas (bulk resin in front of steel bevel) where triangular 6-node elements are used.

Thickness of the adhesive layer is divided into two elements and fine mesh has been adopted in joint area. The mesh gets coarse as it goes far from the mesh refinement area. Size of the mesh is between 0.05 to 0.1 mm in the mesh refinement area, whereas in the composite and steel end it becomes about 10 mm.

Mesh density of the model is selected by carrying out convergence study. The critical part of the finite element model is the middle part where steel and composite sub-straights are connected and maximum stress in adhesive layer is read. Therefore, effective parameters such as number of elements along the thickness of adhesive layer, number of elements along the overlap length and ratio of element size in the middle part are selected for convergence study. Fourteen models with different mesh densities are produced, the characteristics of which are summarized in table 2. Maximum stress in adhesive layer, maximum deflection of the model and total number of elements are reported and suitable mesh density is selected based on the results.

Model ID	M1	M2	M3	Total Number of Elements	Maximum stress in adhesive layer	maximum deflection
1	1	50	8	3716	16.95	0.08557
2	2	50	8	3837	16.77	0.09030
3	3	50	8	3956	14.68	0.09108
4	4	50	8	4075	18.31	0.09191
5	2	50	2	3837	15.78	0.09108
6	2	50	4	3837	16.31	0.09108
7	2	50	6	3837	16.70	0.09108
8	2	50	10	3837	17.27	0.09109
9	2	50	12	3837	17.50	0.09109
10	2	25	8	2862	15.92	0.09108
11	2	40	8	3447	16.65	0.09108
12	2	45	8	3642	16.78	0.09108
13	2	55	8	4032	17.13	0.09109
14	2	60	8	4227	17.33	0.09109

M1: Number of elements along the thickness of adhesive layer
M2: Number of elements along the overlap length
M3: Ratio of element size in the middle part

Table 2: Mesh density study.

More number of elements does not mean more accuracy. Fine mesh density is required in hot points where stress concentration occurs while coarse elements can be used for other parts where the only function is to transfer the load. At both ends of adhesive layer of the middle part fine mesh is used that is achieved by means of ratio of element size (M3 in table 2). Finally model with ID No. 2 is selected for the study. Figures 6 and 7 show the effects of mesh density on maximum stress in adhesive layer and maximum deflection of the model.

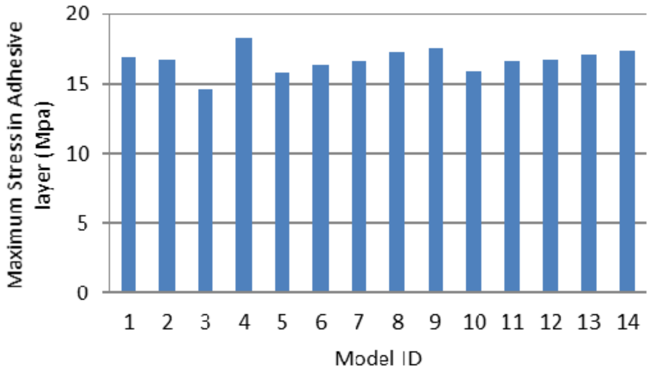

Figure 6: Effect of mesh density on maximum stress in adhesive layer.

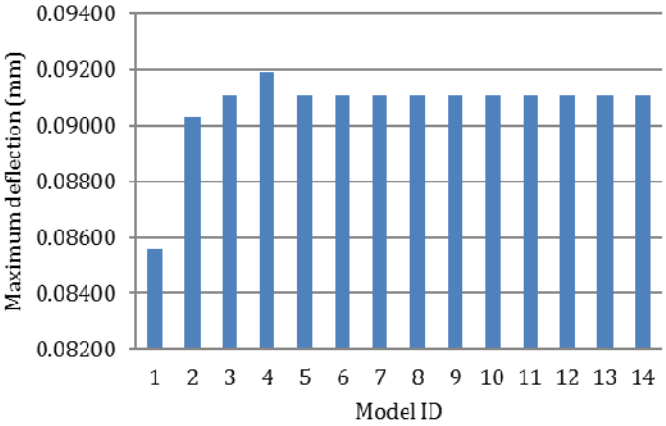

Figure 7: Effect of mesh density on maximum deflection.

2.6 Different Cases for Analysis

Geometric parameters of the reference joint are listed in table 3.

Steel Thickness (mm)	Composite Thickness (mm)			Adhesive Thickness (mm)	Overlap Length (mm)	Stiffness Ratio
	Total	Straight Sublaminate	Curved Sublaminate			
6	12	6	6	0.1	60	0.62

Table 3: Parameters of the reference joint.

Steel thickness and steel bevel angle are 6 mm and 45 degrees respectively and are considered constant for all of the cases. As previously mentioned adhesive thickness, overlap length, composite sublaminates' thickness and stiffness ratio are selected to study. In any case except for the parameter under study all other parameters are kept constant and equal to the parameters of the reference joint. Table 4 to 7 present geometric characteristics of simulated joints in any of the cases.

ID	Steel Thickness (mm)	Composite Thickness (mm)			Adhesive Thickness (mm)	Overlap Length (mm)]	Stiffness Ratio
		Total	Straight Sublaminate	Curved Sublaminate			
OL1	6	12	6	6	0.1	30	0.62
OL2	6	12	6	6	0.1	40	0.62
OL3	6	12	6	6	0.1	50	0.62
OL4	6	12	6	6	0.1	60	0.62
OL5	6	12	6	6	0.1	70	0.62
OL6	6	12	6	6	0.1	80	0.62
OL7	6	12	6	6	0.1	90	0.62
OL8	6	12	6	6	0.1	100	0.62
OL9	6	12	6	6	0.1	110	0.62
OL10	6	12	6	6	0.1	120	0.62

Table 4: Models with different overlap lengths.

ID	Steel Thickness (mm)	Composite Thickness (mm)			Adhesive Thickness (mm)	Overlap Length (mm)	Stiffness Ratio
		Total	Straight Sublaminate	Curved Sublaminate			
AT1	6	12	6	6	0.1	60	0.62
AT2	6	12	6	6	0.15	60	0.62
AT3	6	12	6	6	0.2	60	0.62
AT4	6	12	6	6	0.25	60	0.62
AT5	6	12	6	6	0.3	60	0.62
AT6	6	12	6	6	0.35	60	0.62
AT7	6	12	6	6	0.4	60	0.62
AT8	6	12	6	6	0.45	60	0.62
AT9	6	12	6	6	0.5	60	0.62
AT10	6	12	6	6	0.6	60	0.62

Table 5: Models with different adhesive thicknesses.

ID	Steel Thickness (mm)	Composite Thickness (mm)			Adhesive Thickness (mm)	Overlap Length (mm)	Stiffness Ratio
		Total	Straight Sublaminate	Curved Sublaminate			
SR1	6	6	3	3	0.1	60	0.31
SR2	6	7	3.5	3.5	0.1	60	0.36
SR3	6	8	4	4	0.1	60	0.41
SR4	6	9	4.5	4.5	0.1	60	0.46
SR5	6	10	5	5	0.1	60	0.52
SR6	6	11	5.5	5.5	0.1	60	0.57
SR7	6	12	6	6	0.1	60	0.62
SR8	6	13	6.5	6.5	0.1	60	0.67
SR9	6	14	7	7	0.1	60	0.73

Table 6: Models with different stiffness ratios.

ID	Steel Thickness (mm)	Composite Thickness (mm)			Adhesive Thickness (mm)	Overlap Length (mm)	Stiffness Ratio
		Total	Straight Sublaminate	Curved Sublaminate			
ST1	6	12	4	8	0.1	60	0.62
ST2	6	12	5	7	0.1	60	0.62
ST3	6	12	6	6	0.1	60	0.62
ST4	6	12	7	5	0.1	60	0.62
ST5	6	12	8	4	0.1	60	0.62
ST6	6	12	9	3	0.1	60	0.62
ST7	6	12	10	2	0.1	60	0.62

Table 7: Models with different sublaminate thicknesses.

3 RESULTS AND DISCUSSIONS

Present research aims to establish limits of the design space for a double lap composite-steel joint through a parametric study in order to evaluate the sensitivity of joint performance to geometric changes. As the geometry of the composite-steel joint is complex it requires complicated numerical solutions and therefore finite element analysis is used to measure the stress and stiffness values.

Boundary and loading condition for all cases are the same. Geometries of the joints are presented in tables 4 to 7 above and parameters used to define the reference joint are given in table 3.

Global stiffness, maximum Von Mises stress in the adhesive and the weight are calculated for all geometries and are compared to the reference joint as percentage change from it.

3.1 Overlap Length

Figure 8 shows sensitivity of composite-steel joint to overlap length. 100 percent increase in overlap length from 60 mm to 120 mm will decrease maximum stress in adhesive layer and global stiffness of the joint by 15 and 20 percent respectively. Weight of the joint is directly related to overlap length, the so called 100 percent increase in overlap length will increase the weight by 27.6 percent. Total trend of change in maximum stress in adhesive layer and global stiffness is such that increase in overlap length will cause decrease in these two parameters. Stiffness of the joint changes monotonously but for maximum stress curve there is a change in reduction rate. By increasing overlap length from 30 mm to 80 mm, percentage change in maximum stress is 43 percent while, this change for increasing overlap length's from 80 mm to 120 mm is only 4 percent. As the results are presented in comparative manner only, it can be implied that increasing overlap length decrease maximum stress in adhesive layer of the joint but after a certain amount it will not have significant influence on it.

3.2 Adhesive Thickness

Figure 9 shows the results of changing the adhesive thickness. As the resin is applied as a very thin layer, its variation will not make any significant change in the weight of the joint. This plot shows that the maximum Von Mises stress in the adhesive layer decreases with increasing adhesive thickness. By increasing the adhesive thickness from 0.1 mm to 0.35 mm, 20 percent reduction in maximum Von Mises stress is achieved. Beyond a thickness of 0.35 mm the rate of stress reduction becomes less and only 5 percent stress reduction is gained. S.W. Boyd et al. observed increase in stiffness for composite-steel connection by increasing adhesive thickness, but in present research stiffness of the joint decreases with increase in adhesive thickness. The joint reviewed by S.W. Boyd et al. consists of steel within a GRP/balsawood sandwich, whereas in the present study composite laminate is connected to the steel sheet. Stiffness of the joint decreases as the adhesive thickness increases. Rate of change of stiffness is almost monotonous.

3.3 Stiffness Ratio

Results for changing stiffness ratio of the joint are shown in figure 10. As previously mentioned in order to make variation in stiffness ratio of the joints, composite thickness is the only varying parameter and other parameters influencing stiffness ratio such as steel thickness and mechanical properties of steel and composite are kept constant.

Results show that global stiffness of the joint increases by increase in stiffness ratio, this means if the steel part thickness is considered to be constant, by increasing composite part thickness stiffness of the joint increases. 66 percent increase in stiffness ratio results in 13 percent increase in joint stiffness. Generally, results for maximum stress in adhesive layer show reduction to a certain level and then increase with smaller rate. Increasing stiffness ratio from 0.31 to 0.52 (33 percent) will cause 7 percent decrease in maximum adhesive stress but afterward the same 33 percent increase in stiffness ratio will cause insignificant increase of 3.2 percent in maximum stress. Therefor an optimized stiffness ratio can be found for biomaterial joints.

Increase in stiffness ratio causes increase in weight of the joint as increase in stiffness ratio is acquired by increasing composite part thickness.

3.4 Sublaminate Thickness

It was shown by N.G. Tsouvalis and V.A. Karatzas (through experiments and numerical calculations) that the straight composite sublaminate carries the majority of the axial load and therefore they concluded that in order to distribute the load in the two sublaminates and achieve higher failure loads, thickness of the straight sublaminate should be smaller than that of the other sublaminate.

Figure 11 shows the result for changing straight sublaminate thickness and verifies above claim, it shows decrease in the straight sublaminate thickness causes decrease in maximum stress in adhesive layer. 16.6 percent decrease in straight sublaminate thickness from 7 mm to 6 mm results in 24 percent increase in joint stiffness and 22 percent decrease in the maximum stress in adhesive layer. Reduction of straight sublaminate thickness from 6 mm to 4 mm causes significant increase of about 120 percent in stiffness but as it is obvious from the curve there is negligible change in maximum stress in adhesive layer.

As previously mentioned all geometric parameters rather than the one under study are kept constant, thus composite part thickness is kept constant for all cases and variation of sublaminate thicknesses are such that sum of them remains constant, and therefore there is no change in weight of the joint in evaluation of this parameter.

Table 8 summarizes changes in joint characteristics regarding variation of geometric parameters of the joint:

Item	Change	Maximum stress in adhesive layer	Global stiffness	weight
Overlap length	↑	↓	↓	↑
Adhesive thickness	↑	↓	↓	~ const.
Stiffness ratio	↑	First ↓, then ↑	↑	↑
Straight sublaminate thickness	↑	↑	↓	~ const.

↑: Increase, ↓: Decrease

Table 8: summary of changes in joint characteristics regarding variation of geometric parameters

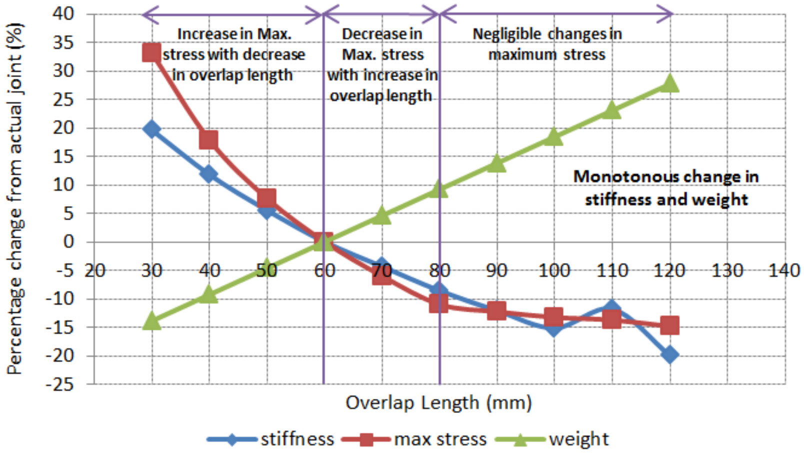

Figure 8: Sensitivity of composite-steel joint to overlap length.

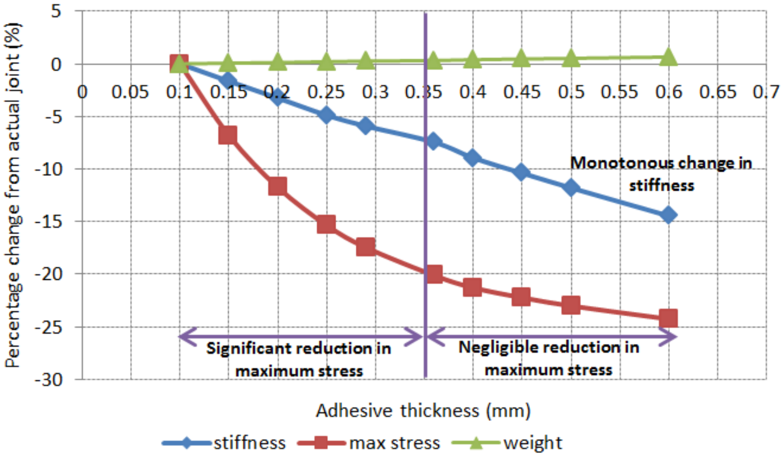

Figure 9: Sensitivity of composite-steel joint to adhesive thickness.

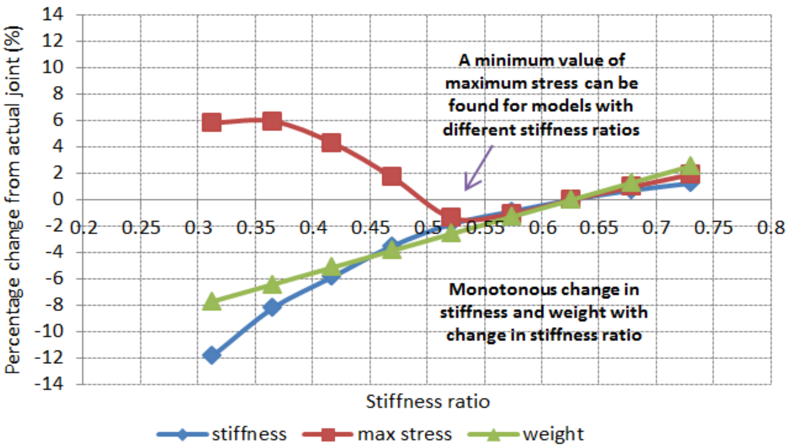

Figure 10: Sensitivity of composite-steel joint to stiffness ratio.

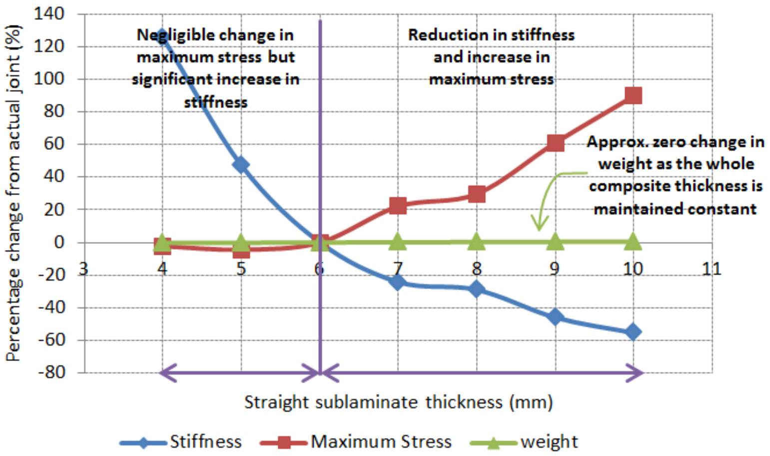

Figure 11: Sensitivity of composite-steel joint to sublaminate thickness.

4 CONCLUSIONS

Modeling of an adhesive composite-steel double lap joint under tensile loading is carried out in finite element environment. In order to evaluate sensitivity of the joint performance to its geometric parameters, results are presented as a series of design curves. In the curves, percentage change in maximum stress in adhesive layer, global stiffness of the joint and its weight are drawn versus variations in selected geometric parameters to assess the influence of geometric parameters in the joint behavior under tensile loading. Adhesive thickness, overlap length, composite sublaminates' thickness and stiffness ratio are selected parameters.

Increase in overlap length will lead to monotonous decrease in global stiffness of the joint. For the maximum stress in adhesive layer of the joint, significant decrease is seen with increase in overlap length but it is effective to a certain amount only. For the investigated joint 50 mm increase in overlap length from 30 mm to 80 mm will decrease the maximum stress in adhesive layer by 43 percent, but after 80 mm overlap length variations become negligible as with 40 mm increase in overlap length only 4 percent decrease in maximum stress is achieved. Effects of adhesive thickness variations on the joint performance are similar to the effects of overlap length variations. Increase in adhesive thickness will cause decrease in maximum stress in adhesive layer and global stiffness. Rate of changes in global stiffness is approximately constant and decrease in is significant to a certain amount beyond which no significant change is observed. For models with different stiffness ratios, design curves show that maximum stress in adhesive layer decreases as the stiffness ratio of the joint increases and after a certain ratio experiences a negligible increase, this means that a minimum value for the maximum stress in adhesive layer can be found by varying stiffness ratio. General trend of the global stiffness curve shows increase by increase in stiffness ratio with nearly a constant rate. Results show decease in thickness of straight sublaminate causes decrease in maximum stress in adhesive layer and increase in global stiffness of the joint.

Increase in overlap length and stiffness ratio of the joint is directly obtained by enlargement of composite laminate and its sublaminates either in length or thickness; therefore these two parameters have direct influence on the joint weight. Due to small thickness of adhesive layer compare to composite and steel parts, its variation has negligible influence on the weight. Negligible change can be reported for the variation of composite sublaminate thickness as the main laminate thickness is kept constant in this case.

Results are presented in comparative manner only and accurate results are not reported. Results show that performance of the joint is fully dependent on geometry of the joint.

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